2006 Final Report to SCEC: Project 06116

Holocene and Latest Pleistocene slip rate of the San Andreas fault in the San Bernardino Valley

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Introduction

We requested funds to complete work at three slip rate sites on the San Bernardino strand of the San Andreas fault. Better understanding of the Holocene to Late Pleistocene slip rate on the San Andreas fault in the San Bernardino Valley is important both in terms of seismic hazard for this rapidly developing area and in terms of understanding fault systems. The San Bernardino segment of the San Andreas fault has one of the most profound differences between geologic and geodetic estimates of the slip rates among faults in southern California. Weldon and Sieh (1985) measured a Holocene slip rate of 24.5 ± 3.5 mm/yr at Cajon Creek (Figure 1a). Meade and Hager (2005) estimate a slip rate of 5.1 ± 1.5 mm/yr using an elastic block model constrained by Global Positioning System (GPS) measurements. In the block model, slip on the Mojave segment of the San Andreas fault is largely transferred to the San Jacinto fault, and slip on the southernmost San Andreas fault, in the Coachella Valley, is largely transferred to the Eastern California shear zone, thus by-passing the San Bernardino segment of the San Andreas fault.

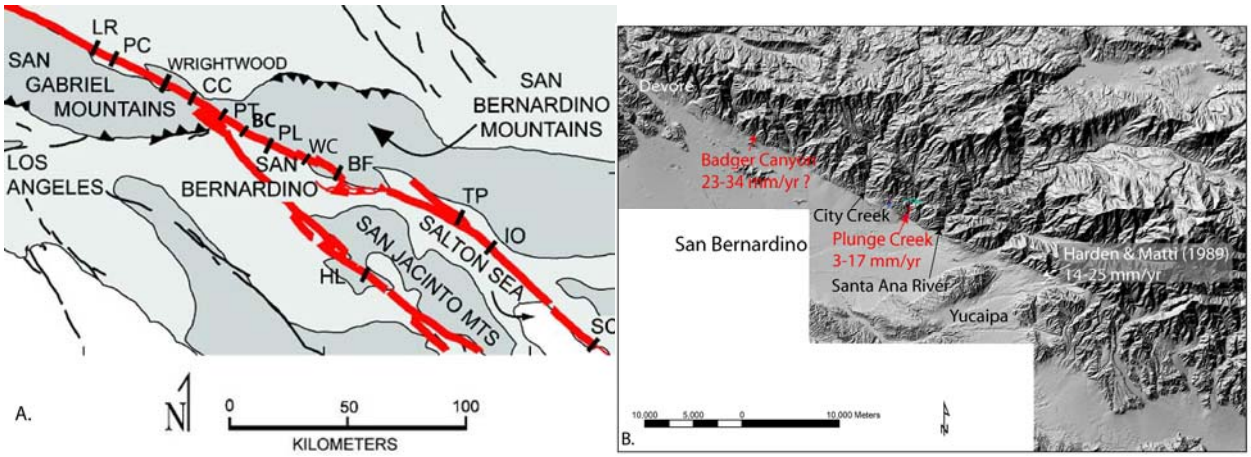

Figure 1: (A) Reference map showing San Andreas and San Jacinto faults in red as well as locations of selected slip rate and paleoseismic sites. Sites mentioned in text include CC, Cajon Creek; BC, Badger Canyon; HL, Hog Lake; PL, Plunge Creek; and WC, Wilson Creek. (B) Digital elevation model showing the location of slip rate sites for the San Bernardino strand of the San Andreas fault. Weldon and Sieh's (1985) slip rate measurement of 24.5 ± 3.5 mm/yr at Cajon Creek is just beyond the northwest corner of the map.

Some of the slip on the northern San Jacinto fault may be transferred to thrusting on the Cucamonga fault, but this probably accommodates only about 5 mm/yr of northwestward motion of the block southwest of the San Jacinto fault (Matti and others, 1985). The remainder of the slip on the northern San Jacinto fault probably transfers to the Mojave segment of the San Andreas fault in the vicinity of Cajon Creek. Unfortunately, the precise location at which this slip transfer occurs is uncertain because the two faults do not actually intersect each other. Rather, they approach each other and then parallel each other, about 2-3 km apart, for a 17-km stretch. Weldon and Sieh (1985) interpreted the slip transfer from the northern San Jacinto fault to the Mojave segment of the San Andreas fault to occur northwest of the Cajon Creek site, thus explaining why the slip rate at Cajon Creek is lower than the 35 mm/yr rate in the Carrizo plain (Sieh and Jahns, 1984). In this model, the Holocene slip rate of the entire San Bernardino segment would be expected to be about 25 mm/yr. If, on the other hand, the part of all of slip transfer occurs southwest of the Cajon Creek site, then the slip rate of the San Bernardino segment of the San Andreas fault could be substantially less than 25 mm/yr. This would significantly reduce the discrepancy between the geologic and geodetic estimates of the slip rate for the San Bernardino segment. Evidence for Holocene slip on the northern San Jacinto fault (Glen Helen strand) terminates about 3 km southeast of the Cajon Creek site (Bortugno, 1986), suggesting that during the Holocene, the primary locus of slip transfer may well have been southeast of Cajon Creek.

The only other published, well-documented slip rate for the San Bernardino strand of the San Andreas fault is at Wilson Creek in Yucaipa, where Harden and Matti (1989) measured a rate of 14-25 mm/yr (Figure 1a,b), with

age control estimated by comparison of soil profiles to dated profiles elsewhere. This estimate allows (but does not require) a San Bernardino strand slip rate that is slower than the rate at Cajon Creek, though still not slow enough to match the rate inferred from geodetic data. A number of workers infer a high slip rate for the San Jacinto fault and thus, either explicitly or implicitly favor the lower end of Harden and Matti's (1989) estimate for the San Bernardino segment of the San Andreas fault (Kendrick et al., 2002; Morton et al., 1986; Savage and Prescott, 1976; Morton and Matti, 1993; King and Savage, 1983; Johnson et al., 1994; Dorsey, 2001). Other investigators favor a model in which the San Andreas fault slips substantially faster than the San Jacinto fault (Weldon and Sieh, 1985; Rockwell and others, 1990; Sharp, 1981; Prentice and others, 1986; Bennett et al., 1996; Lisowski et al., 1991; Keller et al., 1982; Johnson et al., 1994; Humphreys and Weldon 1994). None of these workers, however, has proposed a rate as low as that inferred by Meade and Hager (2005).

Results

We have been working at three slip-rate sites along the San Bernardino strand of the San Andreas fault in an effort to better constrain the geologic slip rate of this segment at several different locations and at several different time scales. Work at the Plunge Creek site is nearly complete and work at the Devore and Badger Canyon sites is still in progress. Funds to complete work at Badger Canyon and to write up the results were requested in our 2007 proposal to SCEC3.

A. Plunge Creek site:

A truncated channel edge of Plunge Creek is preserved on the southwestern (downstream) side of the fault, and it correlates with a terrace riser on the northeast side of the fault (labeled in yellow in Figure 2 below). Geologic mapping indicates that the amount of offset is about 270 (+266, -150) meters along the San Andreas fault. The age of incision of this riser is constrained by radiocarbon dates from the colluvial wedge that buries the high terrace northeast of the fault. Three dates on detrital charcoal from near the base of this colluvial wedge are 29,400 ± 500, 31,400 ± 200 and 36,400 ± 4900 radiocarbon years before present. These dates probably slightly post-date the incision of the terrace riser and abandonment of the upper terrace surface by the amount of time required for progradation of the colluvial wedge. To minimize the impact of reworked charcoal with an inherited age, we use the youngest date, 29.4 ka, which is from a stratigraphic position that appears to be from a portion of the colluvial wedge of similar age to the other two dates. In combination with our preferred 270-meter offset, this yields a preferred right-lateral slip rate of 9.2 mm per radiocarbon-year. Using the minimum and maximum allowable offsets and the 29.4 ka age, allowable slip rates extend from 4 to 18 mm per radiocarbon year. This rate is consistent with geodetic modeling of the San Bernardino segment (Meade and Hager, 2005), and is much lower than the 24.5 mm/yr rate at Cajon Creek and is also lower than the 14-25 mm/yr rate in Yucaipa. A faster slip rate is possible if all three of the dated detrital charcoal samples (including the 29.4 ka sample) were reworked from an older deposit. Preliminary results from two of five OSL samples suggest a younger age for the colluvial wedge, closer to 20 ka, but complete analysis of the OSL samples is still pending. Soil development on the colluvial wedge, including the thickness and abundance of clay films, structure and rubification, is consistent with an age at least as old as that indicated by the radiocarbon dates.

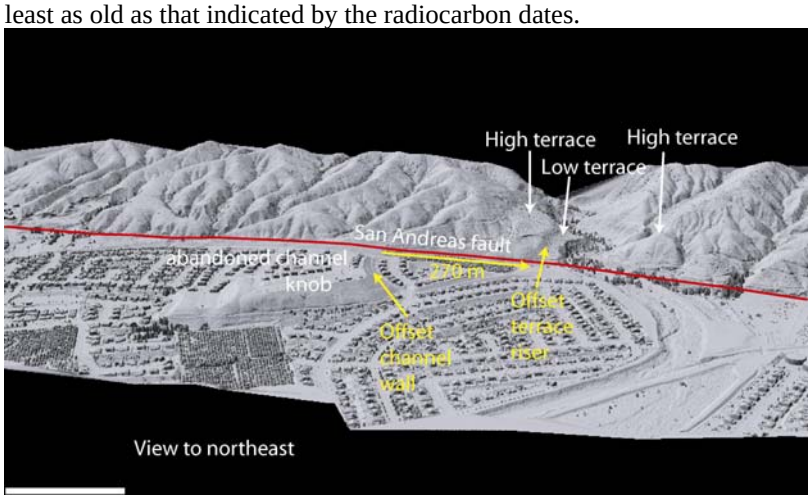

Figure 2: Annotated Airborne Laser Swath image of the Plunge Creek site, showing a truncated channel wall southwest of the fault that is offset from a terrace riser northeast of the fault.

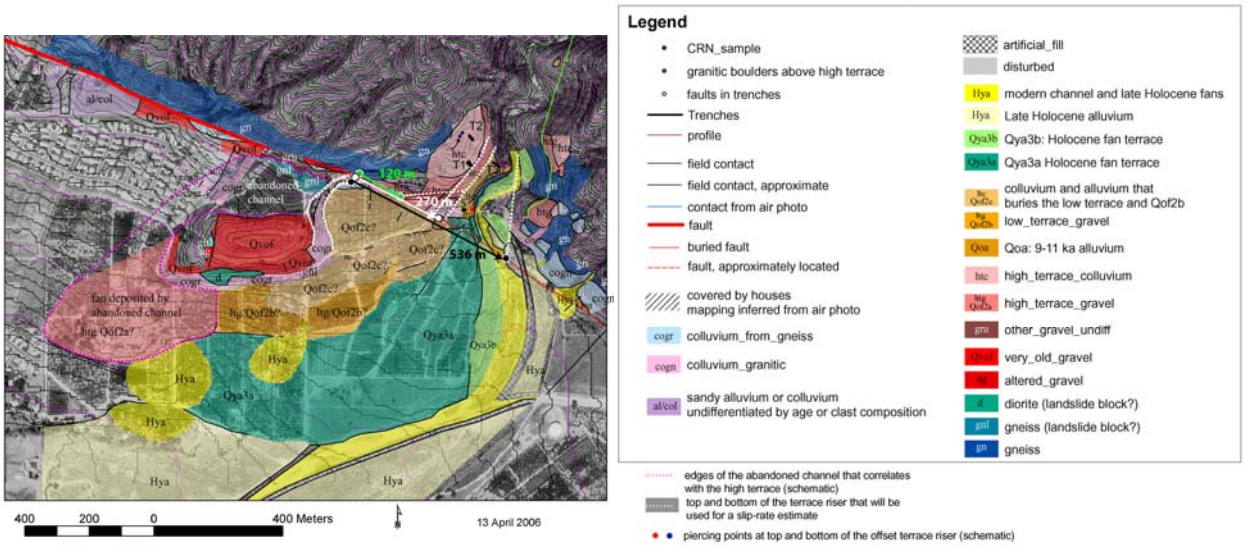

Figure 3: Geologic map of the Plunge Creek site.

B. Badger Canyon site:

In the vicinity of Badger Canyon, in San Bernardino, a large alluvial fan complex, containing fans of at least four different ages, has been offset by the San Andreas fault (Figure 4). With 2006 SCEC funding McGill examined trenches that were excavated by a consulting firm at this site and was able to document the subsurface stratigraphy and to collect samples for radiocarbon and optically stimulated luminescence dating. Katherine Kendrick also described soil profiles on 4 surfaces. The availability of Airborne Laser Swath Mapping (ALSM) data (funded by NSF and conducted by The Ohio State University and U.S. Geological Survey) allowed rapid, accurate measurement of the offsets. The apex of a large alluvial fan (Qf2) has been right-laterally offset about 345-410 meters from Badger Canyon (Figure 4). In addition, the apex of the Qf3 fan appears to be offset about 135 meters, and the riser between the Qf3 and Qf4 fans appears to be offset about 85 meters. Older fan remnants (Qf1) can be brought into alignment by restoring about 690 meters of right-lateral slip. Comparison of the soil profile descriptions from Qf1, Qf2 and Qf3 with dated soils in Cajon Pass, Highland (Plunge Creek), San Timoteo Canyon and Anza, suggest that these fan surfaces are about 30 ka, 12 ka and 4-5 ka, respectively. These very preliminary data suggest slip rates of 23, 29-34 and 30 mm/yr for those three time periods, respectively. These rates are similar to or somewhat higher than the 25-mm/yr rate reported by Weldon and Sieh (1985) to the northwest in Cajon Pass, and are much faster than the 4-18 mm/yr rate estimated to the southeast, at Plunge Creek. It should be noted that the rates estimated for Badger Canyon are very preliminary and may change when the results of pending radiocarbon and optically stimulated luminescence dating become available, and as further work refines the offset estimates and their uncertainties.

C. Devore

Excavations at the Devore site were conducted during January 2007. Several channels in Devore are offset 46-meters. Dating of these channels will provide slip rates for a younger time period than the 85-m and larger offsets at Badger Canyon. These offset channels are expected to be about 2000 years old.

Discussion

We agree with Meade and Hager (2005) that both the high geologic slip rate at Cajon Creek and the low rate implied by geodetic data are robust and are unlikely to be substantially in error. Meade and Hager (2005) also argued that the fact that the San Bernardino segment of the San Andreas fault is likely to be late in its earthquake cycle is insufficient to account for the discrepancy between the geologic and geodetic rates by means of a viscoelastic rheology. Instead they suggested that either the geologic slip rate decreases markedly a short distance south of the Cajon Creek site as a result of slip transfer to the San Jacinto fault, or that the slip rates of the San Andreas and San Jacinto faults (and the eastern California shear zone) have varied in a complementary way over time scales of multiple earthquake cycles, with each fault zone accounting for different proportions of the plate boundary slip during different time periods. The latter model would explain why at the present time strain

accumulation on the San Bernardino segment of the San Andreas fault is lower than its long-term (geologic) average while strain accumulation on the eastern California shear zone is higher than its long-term average. The geodetically inferred slip rate for the San Jacinto fault (11.9 mm/yr, Meade and Hager, 2005) is in good agreement with the geologic slip rate (~12 mm/yr) at Anza over several different time periods ranging from the past 14 ka to the past 50 ka (Rockwell et al., 1990). However, the record of paleoseismic earthquakes on the San Jacinto fault at Hog Lake, near Anza, suggests variations in earthquake frequency over millennial time scales, with 6 surface-rupturing events in the past 1000 years but only four such events in the preceding 2000 years (Rockwell and others, 2003).

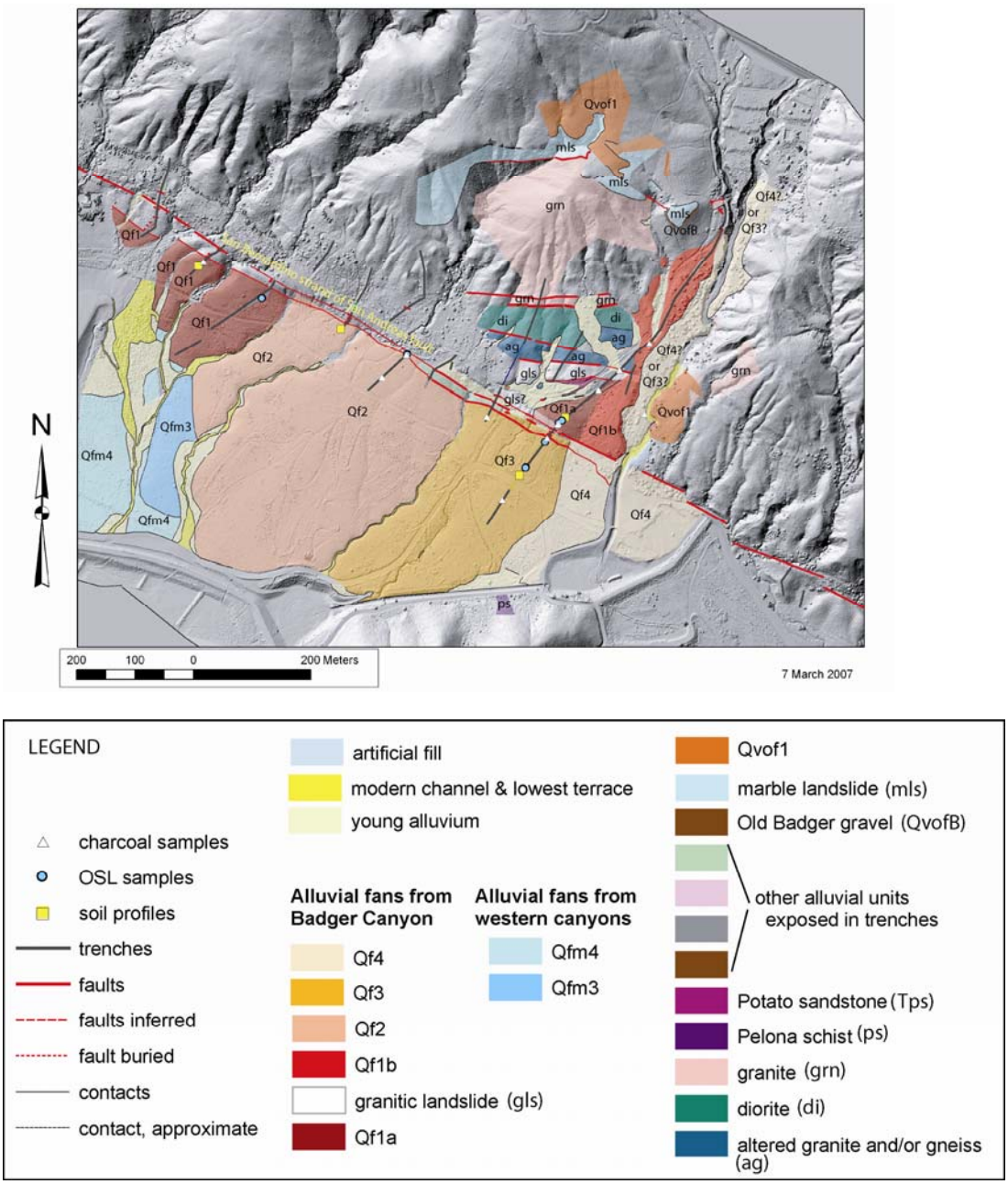

Figure4: Preliminary geologic map of the Badger Canyon site showing the offset alluvial fan complex and numerous trenches excavated by a consulting firm (labeled WT-1, etc.). Locations of samples for are control are shown by white triangles (radiocarbon dating), light blue circles (OSL dating) and yellow squares (soil profile). Base map is an Airborne Laser Swath image.

Results from our SCEC-funded work at Plunge Creek indicate a low slip rate of about 9 mm/yr (allowable range 4-18 mm/yr) over the past ~30,000 years. This unexpected result suggests that the low rate implied by geodetic data may be a persistent characteristic of this portion of the fault rather than a time-dependent phenomenon related to earthquake clustering and shifting of activity between sub-parallel faults over time. The preliminary results from Badger Canyon also do NOT suggest any dramatic variation in slip rate over three different time intervals (30 mm/yr over the past 4-5 ka; 29-34 mm/yr over the past 12 ka, and 23 mm/yr over the past 30 ka). However, the preliminary results from the Badger Canyon site do suggest that for all three time periods the high slip rate measured at Cajon Creek persists for at least 16 km southeastward, well to the southeast of the most likely region in which slip would transfer to the San Jacinto fault. As noted above, however, the age control for the preliminary results from Badger Canyon is based entirely on correlation of soil profiles with dated profiles elsewhere. Radiocarbon dates and optically stimulated luminescence dates for the Badger Canyon site are still pending. Thus the rates may change as the results of more quantitative dating techniques become available. If the preliminary results from the Badger Canyon site are confirmed by other dating techniques, then a mechanism for transfer of slip from the San Bernardino strand of the San Andreas fault to some other fault such as the San Jacinto fault or the Mill Creek strand of the San Andreas fault would need to be found.

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Publications resulting from this grant:

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McGill, S., R. Weldon, II, K. Kendrick and L. Owen, Latest Pleistocene slip rate of the San Bernardino strand of the San Andreas fault in Highland: Possible confirmation of the low rate suggested by geodetic data, *Southern California Earthquake Center annual meeting, Proceedings and Abstracts*, v. 16, p. 131-132, 2006.

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